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Ignition delay in a palm oil and rapeseed oil biodiesel fuelled engine and predictive correlations for the ignition delay period

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Abstract

This paper presents the results of engine tests of biodiesels obtained by transesterification of palm oil and rapeseed oil and with fossil diesel fuel as a reference. The analysis is focused on the determination of the ignition delay and on obtaining a predictive correlation for it. The experiments show no significant difference in cylinder pressures at injection timing for each fuel. With biodiesel slightly lower peak cylinder pressures were observed for most engine conditions. Palm oil and rapeseed oil biodiesel gave shorter ignition delay than fossil diesel fuel due to the higher cetane number for the biodiesels. The ignition delay data were correlated as a function of the equivalence ratio, the mean cylinder pressure and mean temperature over the ignition delay interval. A comparison is made with other available correlations. The ignition delay values estimated by the new correlations are in good agreement with the experiments.

Keywords: Ignition delay, ignition delay correlation, palm oil, biodiesel, rapeseed oil biodiesel.

1. Introduction

The ignition delay in direct injection diesel engines is of great interest because of its direct impact on the heat release, as well as its indirect effect on engine noise and pollutant formation. The ignition delay period is composed of a physical delay, encompassing atomization, vaporization, and mixing, coupled with a chemical delay, a result of pre-combustion reactions in the fuel/air mixture. The two time scales are occurring simultaneously [1-2].

Numerous ignition delay correlations have been proposed. The first correlation was obtained by Hardenberg and Hase [3] and was developed for heavy duty diesel engines. The correlation works over a reasonably wide range of conditions but the correlation covers several experimental

parameters. The developed correlation uses cetane number, temperature, pressure, engine speed and also includes kinetic parameters hard to evaluate in the engine as activation energy, apparent activation energy, and some other adjustable coefficients. It was developed as an empirical formula and is limited because it is a mixture of engine practical parameters like piston mean speed and kinetics parameters more difficult to evaluate. It was also developed for old heavy duty engines and for diesel fuel. This correlation also does not take the equivalence ratio into account.

Assanis [2] compiled in his paper eight empirical formulas for ignition delay correlation obtained using steady flow, constant volume bombs, diesel engines or single droplet experiments and noted a wide range of empirical constants in the correlations. The correlations applied to estimate ignition delay in direct injection diesel engines are often applied outside the temperature-pressure range of their validity or applied for different engines.

The most suitable correlations for diesel engines are those proposed by Assanis and Watson. These empirical correlations are based on pressure and temperature data. Assanis' correlation is very good capturing the transient conditions while Watson's cannot capture it. The main problem is that both correlations were obtained for diesel fuel and cannot be applied to biodiesel, which compared to diesel fuel has important differences in chemical composition, viscosity, density and ignition delay [4,5].

Vasil'ev [6] developed a modification of the Arrhenius equation for multifuels and used it for a two fuel system, but it is not suitable for use with biodiesel. Kavtaradze [7] obtained experimental correlations for natural gas, synthesis gas and conventional diesel fuel. The correlation for diesel fuel was obtained performing experiments in a single cylinder four stroke diesel engine but is only suitable for diesel fuel.

There are reported other correlations experimentally obtained in constant volume bombs, steady flow reactors, rapid compression machines and engines [2,6,7], but they are specific to the tested engines because several engine parameters are involved in the results and they are only validated for fossil diesel fuel. Therefore, this paper focuses on enhancing the understanding of the physical and chemical mechanisms in the pre-ignition phase for biodiesels, as well as providing correlations for the ignition event. Biodiesel is increasingly used, mostly in blended form with

fossil diesel but also in pure form, in order to meet targets set by several governments aimed at increasing the share of renewable in the energy mix (such as the E.U. "2020" Strategic Energy Technology plan). Meeting those targets implies a profound knowledge on the fuel properties so that engines can be suitably adapted for, e.g., biodiesel. An increasing number of papers focus on determining these properties [8-10]. As stated above, the ignition delay is an important engine parameter and is influenced by the fuel properties.

Through arrangement of the Arrhenius equation, Eq. (1) an estimation of the ignition delay τ in milliseconds (ms) can be derived.

$$\tau = Ap^{-n} \exp\left(\frac{E_A}{RT}\right)\phi^{-k} \qquad (1)$$

where: E_A is the activation energy for the combustion process, ϕ is the (fuel to air) equivalence ratio, R the universal gas constant, T and p are temperature and pressure in Kelvin and bar respectively, and n, k and A are adjustable constants. In the kinetic theory n and A are the reaction order and the Arrhenius pre-exponential factor respectively. Both coefficients are normally treated as adjustable coefficients for the model.

Eq. (1) is the inverse of the reaction rate of the global one-step mechanism. Pischinger et al. [11] noted that the inverse pressure dependence in correlations of the form of Eq. (1) can be deduced from elementary reaction kinetics based on a single-stage reaction mechanism.

Some correlations for ignition delay add experimental factors like equivalence ratio [2], concentration of the reactants in the combustion reaction [6,11,12], engine speed [3], etc.

The purpose of this work is to obtain a correlation to predict the ignition delay for biodiesel from two different feedstocks based on the results of the engine tests on a heavy duty diesel engine. The expressions obtained depend on pressure, temperature and equivalence ratio.

2. Experimental setup and methodology

The ignition delay as presented in Eq.(1) depends on pressure and temperature. The ignition delay is by definition, the time interval between the start of fuel injection and the start of combustion [13]. The start of injection is usually taken as the time when the injector needle lifts off its seat. The start of combustion is more difficult to determine precisely. There are some

experimental methods for its determination. Criteria that can be used to quantify the start of combustion in diesel engines include the abrupt change in cylinder pressure gradient, or other pressure-based diagnostics; the light emission detected by a photocell; the temperature rise due to combustion; the combustion of a certain mass of fuel; and the change of slope in the heat release profile. The pressure-based techniques have been shown to be more reliable than the light emission technique. In particular, it is known that a pressure change is often detected before the luminosity detector has observed the appearance of a flame [2]. The pressure based method was selected here for the experimental determination of the ignition delay.

The engines tests were performed with standard diesel fuel and two biodiesels. The engine used was a four stroke diesel engine, type Volvo TD60B turbocharged with six vertical cylinders in a in-line arrangement and water cooled. Table 1 shows the main engine specifications and the valve timing and injection timing. Cylinder n°1 of the engine was equipped with two pressure transducers, one in the cylinder head that measures the cylinder pressure, and another in the cylinder liner, that measures alternately the pressure in the cylinder and crankcase. The positions of the pressure transducers are shown in Fig.1. Both pressure signals were read by a data acquisition card with a resolution of one degree crank angle. The experiments were performed at different torque (M_e). The selected values were 138, 277 and 415 Nm respectively, covering in this order low, medium and high engine loads. The engine speed (n) was varied between 1500-2300 r/min.

For the determination of the start of combustion the first derivative of in-cylinder pressure vs. crank angles degrees (θ) was used. The start of combustion was defined at the moment where the rate of pressure rise $\left(\frac{dp}{d\theta}\right)$ drastically changes. With the start of injection (22 °ca before top dead center) and the start of combustion, the ignition delay is obtained for the different working conditions (load and engine speed). In order to avoid random deviations in measurements, 50 successive cycles were recorded, and the measured values were ensemble averaged.

The measurements for 50 cycles are a compromise between the number of measurements and the level of uncertainty. The 50 cycles measurements are according to the experimental setup for pressure measurements used by many authors, such as Kavtaradze [7].

We compared the ignition delays (obtained from the difference between start of combustion and start of injection) from the individual pressure traces with the ignition delay obtained from the mean pressure trace of 50 cycles to analyze the variability.

The observed variability of the pressure data using 50 cycles was found below 2.5 *bar* for all the experiments and any operational point. This uncertainty in pressure data that is due to the natural variability of cylinder pressure, affects the ignition delay estimated values with maximum variations between 1.2-2.2 %. These levels of uncertainty in ignition delay values are according to Assanis [2] that reported 2 % of variance for ignition delay measuring in-cylinder pressure for 300 cycles. Thus we can conclude that 50 cycles offers a good compromise between accuracy and data to be recorded.

2.1. Theoretical approach

Mean pressures and volumes inside the combustion chamber over the delay interval were obtained from the p-V cycle diagrams for each engine condition. Due to the complexity of measuring instantaneous temperatures in the combustion chamber, the mean temperatures during the delay interval were estimated using the gas law applied for the mean pressure and volume over the delay interval. The in-cylinder mass (trapped conditions) for one cylinder was calculated using the mass air flow and the mass of residual gases. The estimation of the in-cylinder residual gases was based on the calculation of the residual mass fraction (γ_{res}) and the estimation of the molar mass of the residual gases. With (γ_{res}) = residual mass fraction = $\frac{m_{res}}{(m_{air}+m_{fuel})}$.

The apparent molar mass of burnt gases (M_r) was calculated based on the chemical balance of the fuel combustion reaction [13-14] as follows.

The combustion reaction for hydrocarbons can be expressed per mole of oxygen as [13]:

$$\varepsilon\phi C + 2(1-\varepsilon)\phi H_2 + O_2 + \psi N_2 \rightarrow \eta_{CO_2} CO_2 + \eta_{H_2O} H_2O + \eta_{CO} CO + \eta_{H_2} H_2 + \eta_{O_2} O_2 + \eta_{N_2} N_2 \qquad (2)$$

where Ψ = 3,77 is the N/O ratio (for air), $\varepsilon = \frac{4}{4+y}$, y is the molar ratio H/C of the fuel and η_i represents the moles of species i per mole O_2 reactant. The η_i values for different chemical species are tabulated in reference [13]. Eq. (2) was applied for diesel fuel for estimation of the

averaged burnt gases molar mass. The chemical formula used for diesel fuel according to the elemental analysis was $C_{16}H_{30}$.

While equation (2) is for fuels containing C and H only, it can be modified for oxygenated fuels as biodiesels or alcohols (CH_yO_z), the chemical combustion reaction is then expressed as:

$$\phi^*\varepsilon\, C + 2(1-\varepsilon)\phi^* H_2 + O_2 + \psi^* N_2 = \eta_{CO_2} CO_2 + \eta_{H_2O} H_2O + \eta_{CO} CO + \eta_{H_2} H_2 + \eta_{O_2} O_2 + \eta_{N_2} N_2 \qquad (3)$$

where $\phi^* = \phi \cdot \xi$, $\Psi^* = \Psi \cdot \xi$, and z is the molar ratio O/C of the fuel. Eq.(3) was applied for biodiesels. The chemical formula applied in the chemical balance for estimation of the averaged burnt gases molar mass was $C_{18}H_{34}O_2$, based on the elemental analysis of both biodiesels.

$$\xi = \frac{2}{2 - \varepsilon z(1-\phi)} \qquad (4)$$

The averaged burnt gases molar mass for less than 1740 K is expressed as [13]:

$$M_r = \frac{\left(32 + 4\phi(1+2\varepsilon) + 28.16\psi\right)}{\eta_b} \qquad (5)$$

$$\eta_b = (1-\varepsilon)\phi + 1 + \psi \qquad (6)$$

η_b represents the total amount of moles

The coefficients presented in Eq. (5) and (6) are deducted from the combustion balance equation of the fuels analyzed according to Eq. (2) and (3).

Once the molar mass of the residual gases is calculated it is possible to estimate the trapped residual mass and therefore the total mass trapped inside the combustion chamber [13]. Finally, the in-cylinder temperature is calculated based on generalized compressibility charts and the gas law.

Multiple regression analysis was used to obtain the correlations for ignition delay based on cylinder pressure, temperature and fuel-air ratio data. The ignition delay values predicted at different experimental conditions were compared with two well-known correlations. The Watson correlation [15] has a pre-exponential coefficient fixed at 3.45 over all operating points, see Eq. (7):.

$$\tau = 3.45 \frac{\exp\left(\frac{2100}{T}\right)}{p^{1.02}} \qquad (7)$$

The correlation proposed by Assanis [2] is a function of equivalence ratio, with a pre-exponential factor of 2.4, see Eq.(8), that considers the equivalence ratio variations (from 2.6 to 3.8 for the combined pre-exponential factor) as opposed to the Watson correlation where it is fixed at 3.45. This constant value used by Watson would translate into ϕ=0.116 [2,15].

$$\tau = 2.4 \frac{\exp\left(\frac{2100}{T}\right)}{\left(p^{1.02}\phi^{0.2}\right)} \qquad (8)$$

3. Results and Discussion

Figure 2 shows the mean cylinder pressures during the ignition delay period and the maximum combustion pressures (peak pressures) for the three fuels and for the different engine speed and load conditions.

The mean pressure values for the fuels during the delay interval varied between 29-52 *bar*. The uncertainty in the pressure measurements in the tests was less than 0.06 *bar*. There were no significant differences between in-cylinder pressure at injection timing for the analyzed fuels. This is reasonable because at the instant of fuel injection, the in-cylinder pressure concerns only the compression of air and a relative small amount of residual gases, because no fuel is yet present in the combustion chamber. The pressures increase with engine loads as can be expected. For the peak pressure, mainly a decrease for biodiesels is observed due to the shortening of the ignition delay.

From the measurements, the ignition delay for each engine condition was obtained. The experimental results in milliseconds and crank angles degrees for all fuels are shown in Table 2. As observed in Table 2, the ignition delay for biodiesels is generally shorter than diesel fuel. This shortening in ignition delay for biodiesel from different feedstock has been previously reported [16-17]. The main reason is because the cetane number for biodiesel is higher than diesel [4] reducing the size of premixed combustion and thus reducing the ignition delay. Table 2 shows a decrease of the ignition delay when engine speed and torque are increased. The speed increase directly affects the ignition start, shortening the delay period (in ms). The rise in torque increases the pressure and temperature, decreasing the delay time.

The decrease in peak pressure for biodiesels compared to diesel fuel is related to the shortening in ignition delay, because under the same experimental conditions if the delay period is shorter, biodiesel starts the combustion process earlier than diesel and therefore the temperatures and pressures inside the cylinder will be lower during the combustion.

Chemically there are some important differences between diesel fuel and biodiesel. Diesel fuel is composed on average of 75 % saturated hydrocarbons and 25 % aromatics. Furthermore diesel fuel is composed of saturated non-branched molecules with carbons chain lengths ranging from C_{12}-C_{18} and aromatic compounds. Biodiesel is a mixture of fatty acid ethyl esters (ethanol route) with a composition according to the feedstock. Palm oil biodiesel contains a 44 % of $C_{16:0}$ and 39 % of $C_{18:1}$, with a near 50% total amount of unsaturated compounds [5,18]. Besides a slight increase in viscosity for biodiesel which could result in less effective atomization and thus an extended injection delay, the cetane number is related to the chemical composition and is between 40-55 for diesel fuel and 62 for palm oil biodiesel [19]. The measured ignition delays are in accordance with this.

The calculated in-cylinder mass of diesel fuel and palm oil biodiesel are shown in Table 3 and 4 respectively, following the method described before.

The mean cylinder pressures and temperatures during the delay interval for diesel fuel are shown in Table 5. The ignition delay data are correlated as a function of the equivalence ratio and mean cylinder pressure and temperature to obtain an ignition delay correlation using multiple regression analysis. The last column in Table 5 indicates the difference between the measured ignition delay and the predicted ignition delay using the following correlation:

$$\tau = \frac{\exp\left(\frac{950}{T}\right)}{p^{0.24}.\phi^{0.04}} \qquad (9)$$

where T is the mean temperature in Kelvin, p is the mean pressure during the delay interval in bar and ϕ is equivalence ratio.

The pre-exponential and the related pressure factors in Eq. (9) are adjusted constants of the model. The numeric value related to temperature in the exponential factor should be related to the apparent activation energy of diesel fuel under the experimental conditions. Since the activation energy is dependent on the intensity of a molecular collision, it is not used as a regression variable and is only processed as adjustable constants. The proposed correlation for diesel fuel gives adequate results in comparison with the experiments (Table 5), with differences

less than 10 %. Assanis [2] fitted the constants of Eq. (1) in order to minimize the least-square error between measured and correlated ignition delay. Assanis also used an equation type Eq. (1) to fit the experimental data (cylinder pressure, temperature, fuel/air composition and ignition delay).

Using the same procedure, predictive correlations for palm oil and rapeseed oil biodiesel ignition delay are obtained. For palm oil biodiesel:

$$\tau = \frac{\exp\left(\frac{1130}{T}\right)}{p^{0.34} \cdot \phi^{0.02}} \qquad (10)$$

and for rapeseed oil biodiesel:

$$\tau = \frac{\exp\left(\frac{1145}{T}\right)}{p^{0.34} \cdot \phi^{0.06}} \qquad (11)$$

The correlations are similar but with differences in the exponential factor. This term is related to the activation energy, being higher for biodiesel. The comparison between the estimated ignition delay and the experimental values for palm oil biodiesel are shown in Table 6 and for rapeseed oil biodiesel in Table 7.

The mean pressures and temperatures during the delay interval are lower for the biodiesels because of the shorter ignition delay as explained above.

The comparison of the proposed biodiesel correlations and the experimentally obtained ignition delay values are presented in Fig.3. A good prediction of the ignition delay with the proposed correlations (10) and (11) is observed. The differences between experimental values and those predicted by the correlations are range between 0-11.2% for palm oil biodiesel and between 5.3-13% for rapeseed oil biodiesel. The linear regressions shown in Fig.3 represent the residual zero values for both biodiesels. The whiskers represent the 5% interval for each experimental value.

In summary both biodiesel correlations capture satisfactorily the ignition delay trends and magnitudes, under the engine conditions for the tested direct-injection diesel engine.

In the literature no correlations were found for the ignition delay period for biodiesels. The equations (9) and (10) show that the pressure and temperature dependence of the fuel (fossil diesel fuel or biodiesel) on the ignition delay correlation are significantly different.

Correlations for diesel fuel ignition delay can therefore not be extrapolated to biodiesel fuels, as clearly shown in the comparisons of Fig. 4 (comparison of the new predictive correlations for the biodiesels, against measured values and the correlations by Watson and Assanis).

Unlike Watson's correlation, the proposed expressions in both equations (10) and (11) are function of the equivalence ratio. For the presented tests, the equivalence ratio ranges from 0.27 to 0.67, as opposed to Watson correlation where it is fixed at $\phi = 0.116$. The ϕ values in Assanis correlation ranges from 0.10 to 0.67.

The predictive ignition delay correlations (9), (10) and (11) are used in diesel engine simulation models. As explained by Assanis [2], the ignition model consists of this empirical correlation for the ignition delay, which is being evaluated using instantaneous values of cylinder pressure and temperature until the ignition delay period has elapsed, following the procedure of Livengood and Wu [20], i.e. until:

$$\int_{t_s}^{t_s+\tau_{ID}} \frac{dt}{\tau_{ID}(t)} = 1.0 \qquad (12)$$

In the obtained models, the chemical reactions occurring during the ignition delay are expressed by a simple one-step mechanism of the Arrhenius type, in which ignition is assumed to be reached when the concentration of certain species exceeds a threshold for each fluid element whose state may change according to the details of mixing. Basically, this assumption is equivalent to assume the Livengood-Wu integral to reach a value of 1, which has been often applied to predict the ignition delay under time-dependent pressure and temperature from the delay data gained at a fixed pressure and temperature [21].

The derived correlations (10-11) may be used for the improvement of the characteristics of diesel engines operated on palm and rapeseed oil biodiesel, through the use of a diesel engine simulation model with an ignition delay sub-model based on these correlations. Such an ignition sub-model mostly consists of an empirical correlation for ignition delay, which is evaluated during a simulation run using instantaneous calculated values of cylinder pressure and temperature (using conservation of mass and energy, and the ideal gas law) until the ignition delay period has elapsed, as is explained by Livengood [20].

The obtained models to predict the ignition delay could be refined performing more experiments on different engines. In the present work the in-cylinder temperature values are based on calculations taking into account the residual in-cylinder mass of gases and the gas law. The estimation of the residual in-cylinder mass of gases can be improved using a gas dynamic model of the combustion process.

4. Conclusions

In this study correlations were developed for predicting the ignition delay of two biodiesels in a direct injection diesel engine. Cycle-resolved cylinder pressure traces were recorded and analyzed for 50 successive cycles, for a number of engine tests covering a wide range of engine loads and speeds. The start of combustion was estimated using the pressure rise curves. At each condition, ignition delay was determined as the difference between start of injection and start of combustion. Biodiesels from palm and rapeseed oils show shorter ignition delay than diesel fuel. Application of multiple regression to fit the experimental data based on global reaction rate theory, let to obtain correlations for ignition delay exhibiting a dependence on equivalence ratio, pressures and temperatures in the combustion chamber. The new proposed correlations for biodiesels have been compared against the Watson et al. and Assanis et al. correlations (for fossil diesel). The comparison with ignition delay measurements show that the new correlations predict ignition delay for biofuels better than the available correlations for diesel fuel.

It is therefore concluded that the new correlations significantly improve the ignition delay predictiveness for biodiesels in a wide range of parameters such as the cylinder pressures and temperatures at injection, the equivalence ratio, and the engine load and speed conditions.

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Figure and table captions

Figure captions

Table captions

Table1

feature	values
connecting rod length	0,23 *m*
bore	0,098 *m*
stroke	0,12 *m*
compression ratio	16
swept volume per cylinder	913,12 cm^3
total swept volume	5479 cm^3
inlet valve opens	18º before TDC
inlet valve closes	234º after TDC
exhaust valve opens	120º after TDC
exhaust valve closes	16º after TDC
injection starts	22º before TDC

Table2

n (r/min)	Me (Nm)	palm oil BD (ms)	palm oil BD (°ca)	rapeseed oil BD (ms)	rapeseed oil BD (°ca)	diesel fuel (ms)	diesel fuel (°ca)
1500	138	1.44	13	1.56	14	1.44	13
1900		1.14	13	1.14	13	1.40	16
2300		1.16	16	1.09	15	1.30	18
1500	277	1.33	12	1.44	13	1.56	14
1900		1.05	12	1.23	14	1.32	15
2300		1.01	14	1.16	16	1.16	16
1500	415	1.22	11	1.33	12	1.33	12
1900		0.96	11	1.14	13	1.32	15
2300		0.94	13	0.94	13	1.16	16

Table3

Me (Nm)	n (r/min)	n_p	γ_{res}	ϕ	m_{res} (g)	m_T (g)
138	1500	1.33	0.05	0.31	0.05	1.07
	1900	1.33	0.04	0.33	0.04	1.04
	2300	1.35	0.04	0.30	0.05	1.19
277	1500	1.33	0.03	0.50	0.03	1.12
	1900	1.29	0.03	0.49	0.04	1.15
	2300	1.32	0.03	0.43	0.05	1.36
415	1500	1.27	0.02	0.64	0.03	1.23
	1900	1.28	0.02	0.62	0.03	1.27
	2300	1.31	0.03	0.52	0.04	1.54

Table4

Me (Nm)	n (r/min)	n_p	γ_{res}	ϕ	m_{res} (g)	m_T (g)
138	1500	1.35	0.05	0.34	0.05	1.07
	1900	1.34	0.05	0.28	0.05	1.05
	2300	1.31	0.04	0.28	0.05	1.19
277	1500	1.28	0.03	0.46	0.04	1.13
	1900	1.31	0.03	0.42	0.04	1.15
	2300	1.31	0.03	0.43	0.04	1.35
415	1500	1.28	0.03	0.63	0.04	1.24
	1900	1.31	0.03	0.56	0.03	1.27
	2300	1.31	0.03	0.53	0.04	1.54

Table5

Me (Nm)	n (r/min)	$\overline{p}$ (bar)	$\overline{T}$ (K)	ϕ	τ_{exp} (ms)	τ_{calc} (ms)	$\frac{\tau_{exp}-\tau_{calc}}{\tau_{exp}}$ (%)
138	1500	29.1	777	0.31	1.44	1.58	-10.1
	1900	31.6	862	0.33	1.40	1.37	1.9
	2300	36.7	874	0.30	1.30	1.31	-0.8
277	1500	32.1	819	0.50	1.56	1.43	8.6
	1900	34.8	844	0.49	1.32	1.35	-2.5
	2300	42.4	877	0.43	1.16	1.24	-7.2
415	1500	36.0	838	0.64	1.33	1.34	-0.6
	1900	40.6	881	0.62	1.32	1.23	6.7
	2300	49.8	892	0.52	1.16	1.17	-0.5

Table6

Me (Nm)	n (r/min)	$\bar{p}$ (bar)	$\bar{T}$ (K)	ϕ	τ_{exp} (ms)	τ_{calc} (ms)	$\frac{\tau_{exp}-\tau_{calc}}{\tau_{exp}}$ (%)
138	1500	29.3	734	0.34	1.44	1.51	-4.9
	1900	30.5	858	0.28	1.14	1.20	-5.1
	2300	35.2	864	0.28	1.16	1.13	2.6
277	1500	31.5	828	0.46	1.33	1.23	7.5
	1900	33.3	850	0.42	1.05	1.17	-11.2
	2300	41.3	872	0.43	1.01	1.05	-3.8
415	1500	32.5	825	0.63	1.22	1.22	0.0
	1900	38.5	879	0.56	0.96	1.06	-10.2
	2300	48.0	901	0.53	0.94	0.95	-1.3

Table7

Me (Nm)	n (r/min)	$\overline{P}$(bar)	$\overline{T}$ (K)	ϕ	τ_{exp} (ms)	τ_{calc} (ms)	$\frac{\tau\ exp-\tau\ calc}{\tau\ exp}$ (%)
138	1500	29.9	787	0.31	1.56	1.45	7.2
	1900	32.0	857	0.27	1.14	1.27	-11.1
	2300	35.7	860	0.30	1.09	1.21	-10.7
277	1500	33.0	834	0.50	1.44	1.25	13.0
	1900	37.1	858	0.46	1.23	1.16	5.3
	2300	42.9	891	0.43	1.16	1.06	8.7
415	1500	36.4	830	0.67	1.33	1.20	9.9
	1900	41.8	875	0.61	1.14	1.07	6.0
	2300	48.4	880	0.50	0.94	1.02	-8.9

Figure1
Click here to download high resolution image

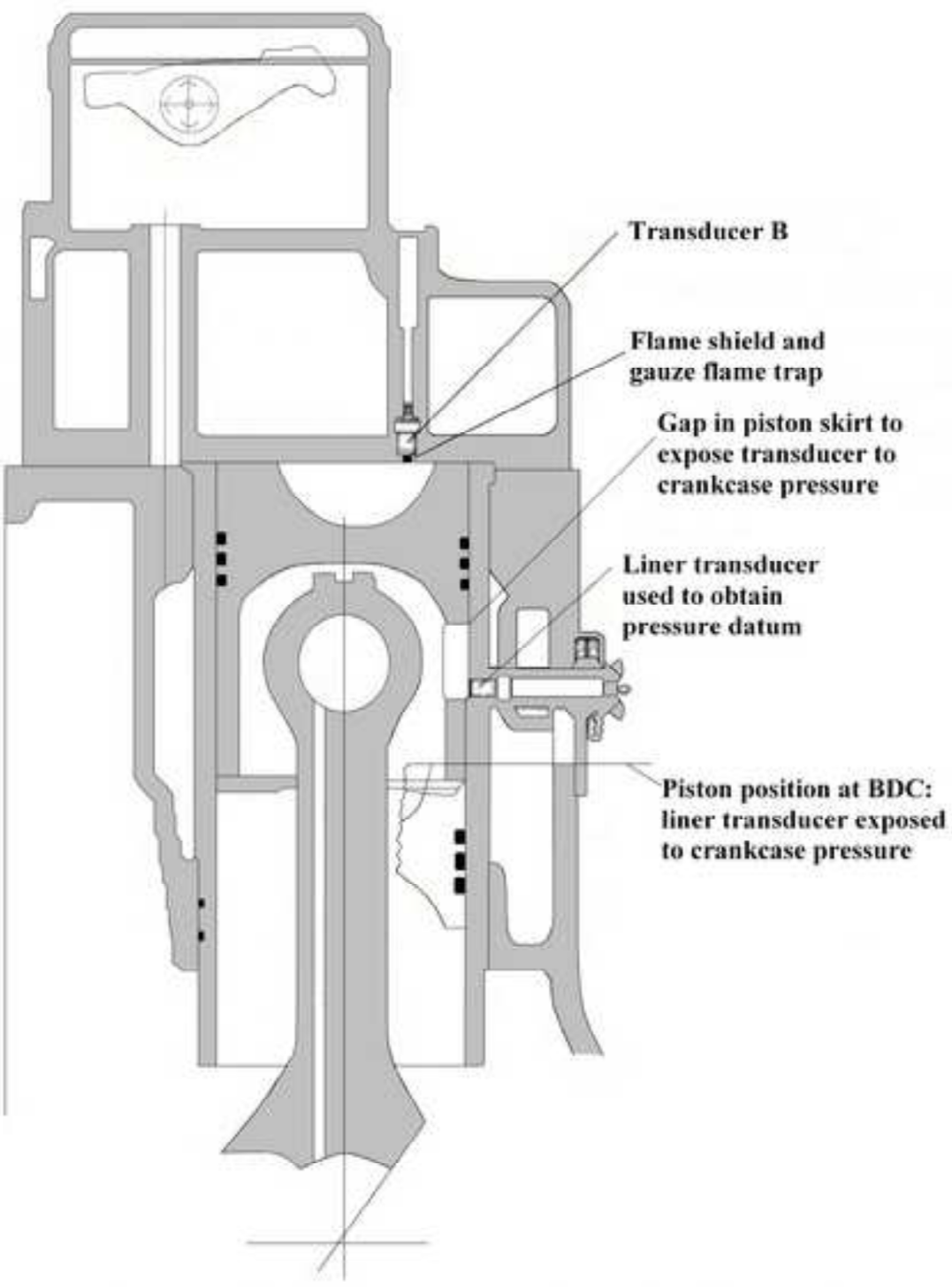


Figure2

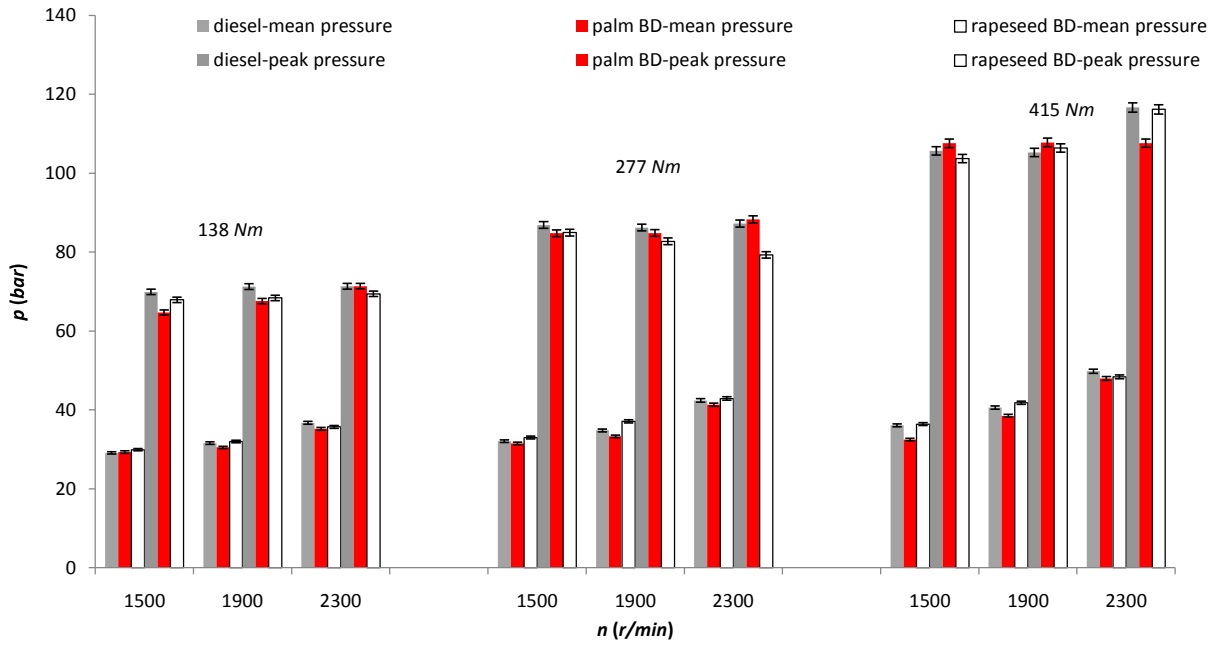

diesel-mean pressure
palm BD-mean pressure
rapeseed BD-mean pressure
diesel-peak pressure
palm BD-peak pressure
rapeseed BD-peak pressure
138 Nm
277 Nm
415 Nm
p (bar)
n (r/min)
0
20
40
60
80
100
120
140
1500
1900
2300

Figure3

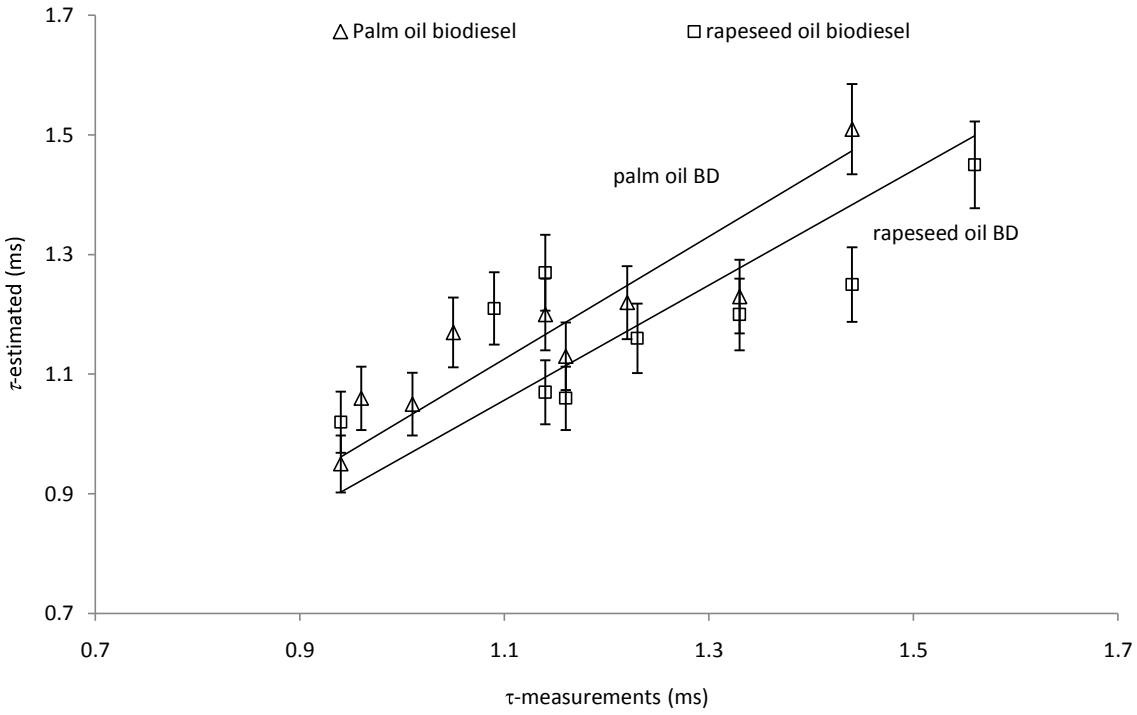
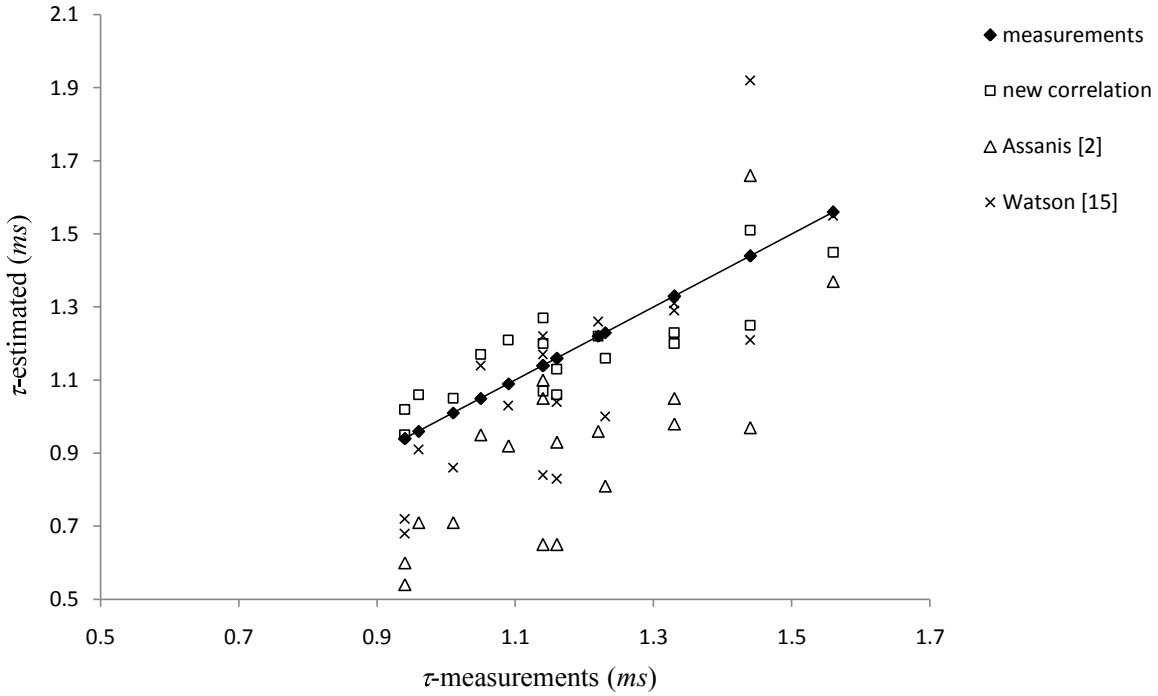

Palm oil biodiesel
rapeseed oil biodiesel
palm oil BD
rapeseed oil BD
τ-estimated (ms)
τ-measurements (ms)
1.7
1.5
1.3
1.1
0.9
0.7
0.7
0.9
1.1
1.3
1.5
1.7

Figure4


2.1
1.9
1.7
1.5
1.3
1.1
0.9
0.7
0.5
τ-estimated (ms)
0.5
0.7
0.9
1.1
1.3
1.5
1.7
τ-measurements (ms)
measurements
new correlation
Assanis [2]
Watson [15]